

Current and Near-term Future Measurements of the Orbital Debris Environment at NASA.

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Abstract

The NASA Orbital Debris Program Office places great emphasis on obtaining and understanding direct measurements of the orbital debris environment. The Orbital Debris Program Office's environmental models are all based on these measurements. Because OD measurements must cover a very wide range of sizes and altitudes, one technique realistically cannot be used for all measurements. In general, radar measurements have been used for lower altitudes and optical measurements for higher altitude orbits. For very small debris, *in situ* measurements such as returned spacecraft surfaces are utilized. In addition to receiving information from large debris (> 5-10 cm diameter) from the U.S. Space Surveillance Network, NASA conducts statistical measurements of the debris population for smaller sizes. NASA collects data from the Haystack and Goldstone radars for debris in low Earth orbit as small as 2-4 mm diameter and from the Michigan Orbital DEbris Survey Telescope for debris near geosynchronous orbit altitude for sizes as small as 30-60 cm diameter. NASA is also currently examining the radiator panel of the Hubble Space Telescope Wide Field Planetary Camera 2 which was exposed to space for 16 years and was recently returned to Earth during the STS-125 Space Shuttle mission. This paper will give an overview of these on-going measurement programs at NASA as well as discuss progress and plans for new instruments and techniques in the near future.

1. Introduction

One of the important uses of space surveillance is understanding and monitoring the orbital debris environment. Earth orbiting spacecraft have become an integral part of our everyday lives. We depend on them for communications, weather information, scientific research, and national security. A real and growing concern for the safety and reliability of these satellites is the threat from collision with other orbiting objects including space debris. Even small particles can damage, degrade, or destroy spacecraft due to the very high velocities involved in a collision, on the average about 11 km/sec. The first accidental collision between two intact satellites in February 2009 illustrates the danger to operational spacecraft from human made and natural space debris.

This paper endeavors to provide a summary of activities of the NASA Orbital Debris Program Office (ODPO) to characterize the orbital debris environment through measurements and to discuss some future plans.

2. Measurements of the Orbital Debris Environment

The NASA ODPO places great emphasis on obtaining and understanding direct measurements of the orbital debris environment. The ODPO's environmental models are all based on these measurements.

Because orbital debris measurements must cover a very wide range of sizes and altitudes, one technique realistically cannot be used for all measurements. In general, radar measurements have been used for lower altitudes and optical measurements for higher altitude orbits. For very small debris, *in situ* measurements such as returned spacecraft surfaces are utilized.

2.1 U.S. Space Surveillance Network

In the U.S., the Department of Defense (DoD) maintains a catalog and ephemeris of orbital objects and debris for sizes as small as 5- to 10-cm diameter in LEO and about 1-m diameter in GEO using its worldwide network of radar and optical sensors that comprise the U.S. Space Surveillance Network (SSN) (see Figure 1).



Figure 1. U.S. Space Surveillance Network

The number of objects in the catalog has grown over the years (see Figure 2). The number has grown significantly in recent years due to the Fengyun 1C event in 2006 and the Iridium/Cosmos collision in 2009. In addition to cataloged objects, the SSN is also routinely tracking a significant number of objects which have not yet been entered into the catalog. At the time of this writing, the SSN is tracking an additional ~5000 objects for a total on-orbit population of ~21,500 tracked objects. Trajectories of these objects can be predicted and used to calculate potential conjunctions with operational satellites, including crewed spacecraft such as the International Space Station, the Space Shuttle, Soyuz, and the Shenzhou spacecraft.

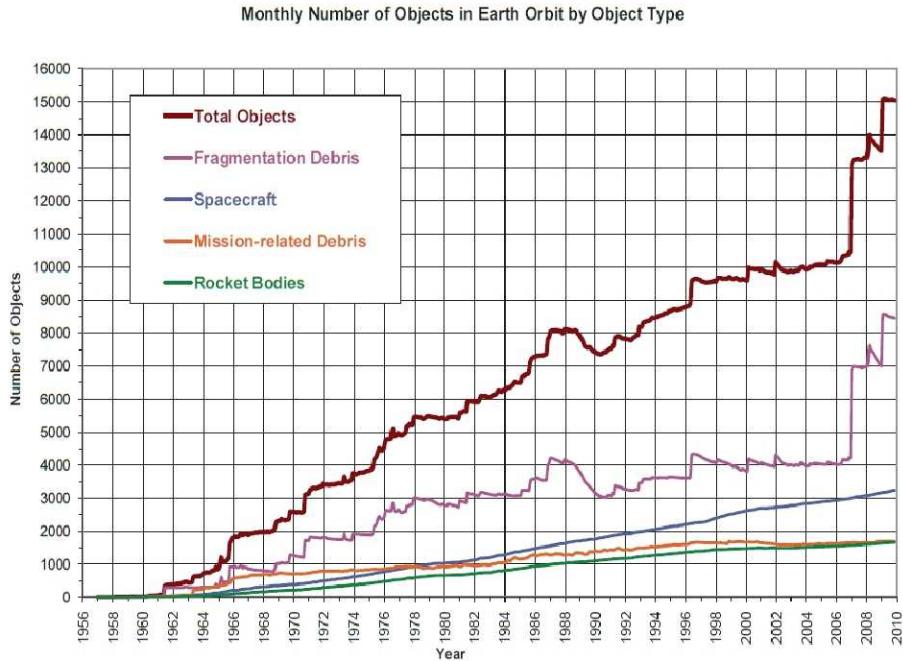


Figure 2. – Growth of the SSN catalog¹.

NASA performs measurements of the environment for debris sizes that are too small to be included in the SSN catalog. The measurements are intended to statistically characterize the orbital debris environment, rather than to create and maintain a catalog of these small objects.

2.2 Radar Measurements

To obtain debris data down to 2 mm in diameter, NASA has been utilizing radar observations of the LEO debris environment from the NASA Jet Propulsion Laboratory (JPL) Goldstone Deep Space Network radars, the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL) Haystack LRIR, and the MIT/LL Haystack Auxiliary, or HAX radar. The Goldstone radar is located in southern California's Mojave Desert at a latitude of 35.2° and the Haystack and HAX radars are co-located in Massachusetts near Boston at a latitude of 42.6°. Unlike Goldstone, whose primary mission is to monitor deep space probes, Haystack and HAX are both extensively utilized for debris observations, typically collecting several hundred hours each year.

Both Haystack and HAX are monostatic radars that measure the range, the radial velocity, the principal polarization RCS, the orthogonal polarization RCS, and the position within the radar beam using a monopulse system. For debris observations, the radars statistically sample the debris populations by operating in a staring, or "beam park," mode. In this mode, the antenna is pointed at a specified elevation and azimuth and remains there while debris objects randomly pass through the field of view (FOV) of the radar beam. This operational mode provides a fixed detection area important to the measurement of the debris flux, or number of objects detected per unit area per unit time, which is the defining quantity for debris risk analysis.

The HAX radar has less sensitivity than Haystack, but has a larger beamwidth. Both radars are capable of full-sky pointing. The Goldstone radar operates in a bi-static mode in conjunction with a second, smaller antenna a few hundred meters from the main antenna. It can measure the range, radial velocity, and principal polarization RCS of debris. Until recently, the Goldstone radar could only point near the zenith for debris observations. Haystack's availability, along with its very high sensitivity, makes it the primary source of data for characterizing the small debris environment.

The Goldstone radar generally observes objects at altitudes from 300 km to 3200 km with near-z zenith pointing. Commonly, both Haystack and HAX collect data by pointing the radars east at 75° elevation.

Sometimes, Haystack points south at 10° elevation or at 20° elevation in order to sample debris from lower inclination orbits. With 75° east-pointing, both radars observe debris from 350 km to 1800 km. The overlapping size regions among the radars allow a continuous measurement of debris with diameters from less than 1 cm to several meters. Moreover, the overlapping size regions allow comparisons in order to understand systematic and statistical variations in the data. Figure 3 shows cumulative debris flux versus diameter from altitude 1000 km to 1200 km for all three radars.

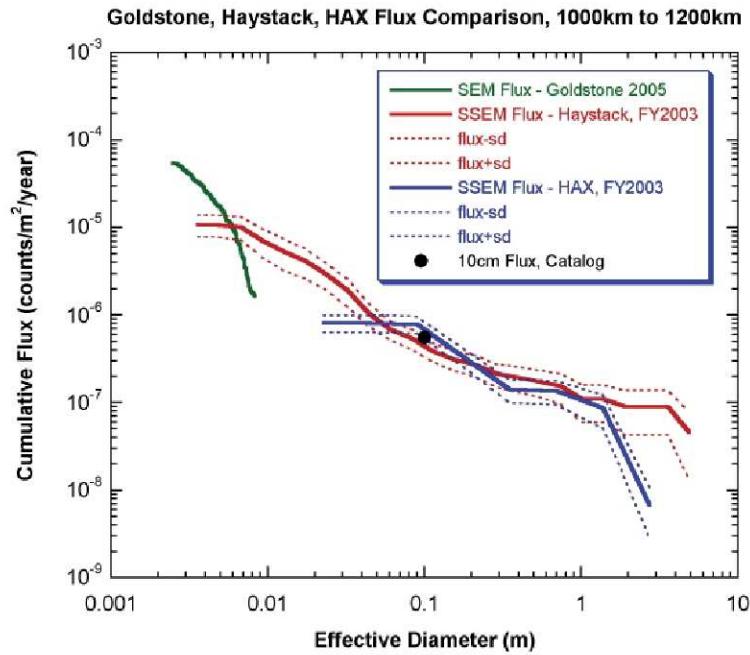


Figure 3. - Comparison of orbital debris flux from three radars.

Note: The SEM and SSEM are the Size Estimation Model² and the Statistical Size Estimation Model³. Both models relate radar cross section (RCS) to physical size.

2.3 Optical Measurements

In 2002, NASA began observations using the MODEST telescope, a 0.6/0.9 m Curtis Schmidt telescope operated by the University of Michigan located at Cerro Tololo Inter-American

Observatory (CTIO) in Chile. It has a $1.3^\circ \times 1.3^\circ$ FOV, uses a 2048 x 2048 pixel thinned SITE CCD (Peak QE 90%). Each pixel covering 2.3 arc seconds and the system is capable of detecting 19th magnitude objects in a 5-s integration that corresponds to an ~12-cm diameter, 0.175 albedo object at 36,000 km, assuming a diffuse Lambertian phase function.

Observations are made at a single right ascension and declination over an observing period. Observations are targeted near to the Earth shadow at GEO, so that the target objects will have minimum solar phase angle, but still are clear of the shadow. This is done to (hopefully) maximize the brightness of the objects. In addition, the observations are usually chosen to avoid the plane of the Milky Way as much as possible, for the multitude of stars in that region of the sky can easily mask the dim GEO objects, or overwhelm the automated object detection algorithm.

Once the field centers are determined, the data are run through a code that determines the probability of detecting an object in a specific orbit while in that FOV and at that specific time⁴. Such a probability chart is shown in Figure 4. The different colors represent the probability of detection. The redder the color, or the closer the probability is to 1, the greater the likelihood an object in that orbit was detected. Overlaid on the probability chart are the actual detections for the 3 years of data. The solid diamonds represent correlated targets (objects which are already tracked and cataloged by the SSN) and the open circles represent uncorrelated targets. Using this analysis, a total population can be derived from the measurements.

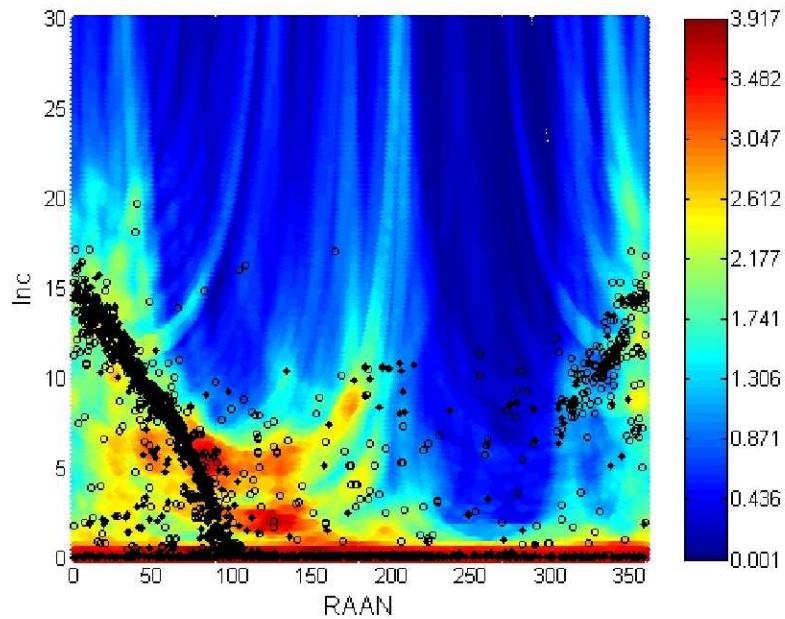


Figure 4. - Probability of finding specific orbits from fields observed by the telescope.

2.4 In Situ Measurements

2.4.1 Space Shuttle

Debris smaller than about 2-3 mm cannot be detected easily by ground-based radars or optical telescopes. Space-based in-situ measurements, the study of surfaces that have been exposed to space in Earth orbit, have been the only means to describe sub-millimeter debris populations. All spacecraft collide with very small orbital debris particles and meteoroids; consequently, spacecraft surfaces returned to Earth are found to have many small craters resulting from hypervelocity impacts.

One of the primary sources of data in this size regime is the Space Shuttle. After each flight, the Shuttle windows are examined for small impacts. Hypervelocity testing of Shuttle window material has been done in order to relate impact crater size to the size of the impacting debris. Also, for each Shuttle mission, the time history of the orientation of the Shuttle while it is on orbit is known. From these data, the population of small debris particles can be estimated using certain assumptions about the orbit distribution of the debris.

Figure 5 shows one of the largest impacts seen on the Shuttle. This feature was found on the Shuttle radiator located inside the payload bay doors on STS-115.

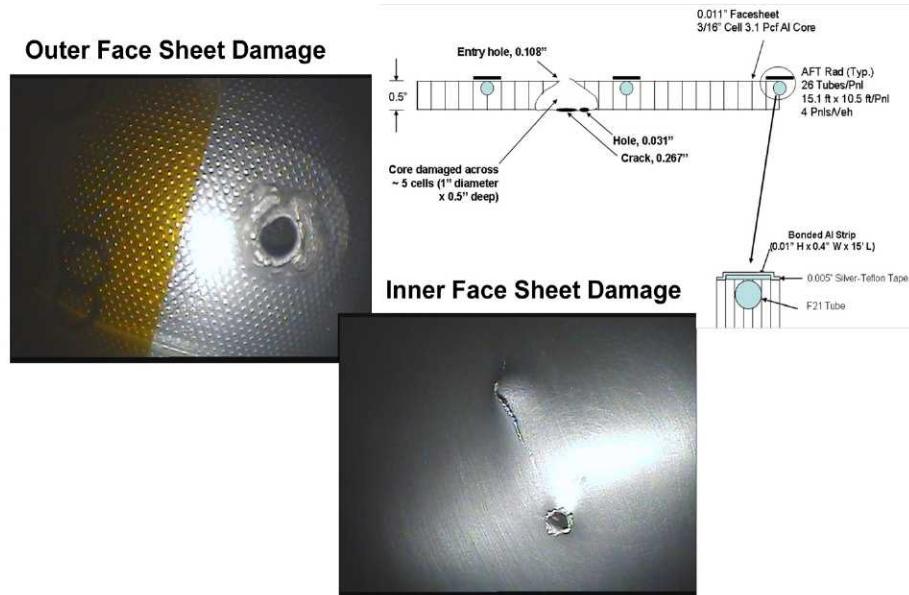


Figure 5. – Impact feature seen on STS-115 radiator. The entry hole is 2.7 mm diameter which created a 2.5 cm void in the radiator's honeycomb structure. Hypervelocity impact tests conducted at the NASA White Sands Test Facility on realistic, simulated radiator panel material suggest that the particle size was approximately 1.5 mm to 2.0 mm in diameter, assuming that the particle was orbital debris.

2.4.2 Hubble Wide Field Planetary Camera 2 (WFPC2) Radiator

The STS-125 astronauts retrieved the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) during a very successful and final servicing mission to the HST in May, 2009. The radiator attached to WFPC2 has dimensions of 2.2 m by 0.8 m. Its outermost layer is a 4-mm-thick aluminum, curved plate coated with white thermal paint. This radiator has been exposed to space since the deployment of WFPC2 in 1993. Due to its large surface area and long exposure time, the radiator serves as a unique witness plate for the micrometeoroid and

orbital debris (MMOD) environment between 560 and 620 km altitude. This is a higher altitude range than is normally flown for Shuttle missions.

The NASA Orbital Debris Program Office is leading an effort, with full support from the NASA Hypervelocity Impact Technology Facility, NASA Meteoroid Environment Office, and NASA Curation Office, to conduct an MMOD impact survey of the WFPC2 radiator. The goal is to use the data to validate or improve the near-Earth MMOD environment definition. This effort is also very well supported by the HST Program located at the NASA Goddard Space Flight Center.

From the on-orbit images taken during the last two servicing missions, 20 large MMOD impacts are clearly visible (Figure 6)⁵.

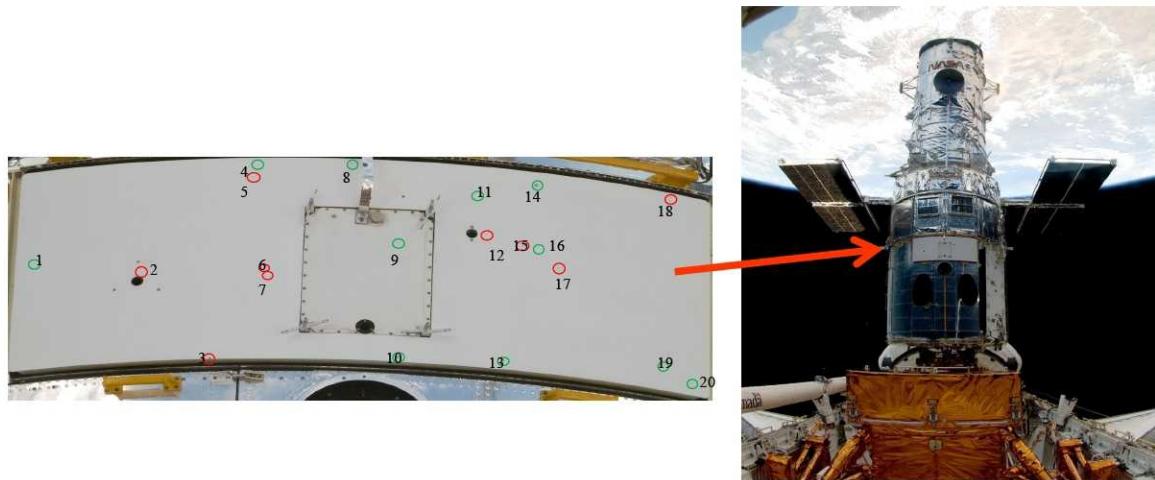


Figure 6. 20 largest impact features seen on the Hubble WFPC2 camera radiator. The red circles are features identified during a 2002 repair mission. Impact features in green circles were created between 2002 and 2009.

The initial MMOD impact inspection of the WFPC2 radiator was completed in September 2009. Two instruments were used during the 6-week inspection at GSFC – a laser scanner for a quick map of the distribution of impact features on the surface and a digital microscope for detailed two- and three-dimensional imagery of individual impacts. In addition, a laser template projector was designed and set up to record the coordinates of individual impact features. The inspection was limited to features larger than about 300 µm across, because this is approximately the threshold for the smallest MMOD particles that are important for satellite impact risk assessments (see Figure 7).

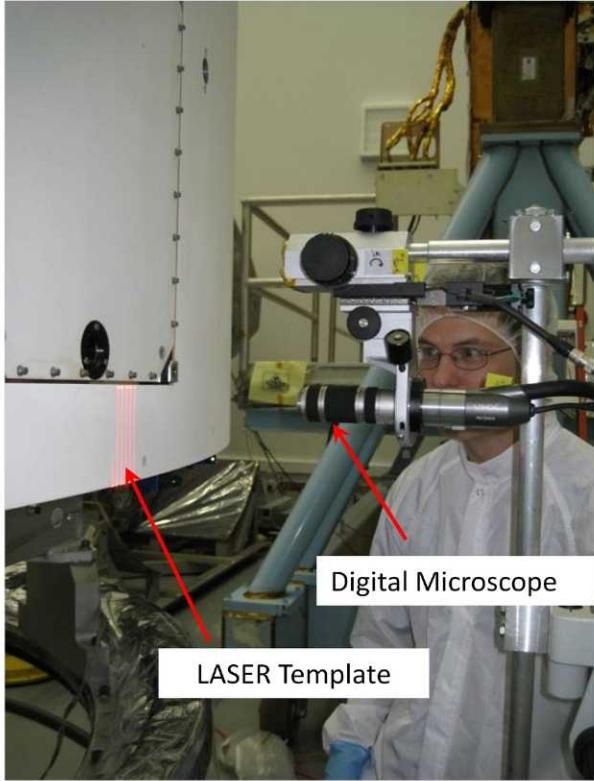


Figure 7. Inspection of the Hubble WFPC2 radiator. Visible are the LASER template for documenting the location of the feature and the Digital Microscope.

By the end of the inspection, a total of 685 MMOD impact features were identified and documented. The largest one has a crater diameter of 1.6 mm with a surrounding spall zone about 1.4 cm across (on the painted radiator surface). The outermost layer of the radiator is a 4-mm thick aluminum plate coated with thermal control paint. The majority of the documented impacts did not penetrate the paint layer. An additional 200 or so non-impact features, such as surface contamination and tool marks, were also observed and documented.

The processing and analysis of the crater images are currently underway. Figure 8 shows the image (top) and the two-dimensional cross-section profile (bottom) of one of the largest impacts⁶. The damage shown is ~1.4 mm across (distance between "C" and "D") with a spall zone about twice as big. The green line labeled by "A" defines the top surface of the paint while the green line labeled by "B" indicates the bottom of the crater in aluminum. The distance from "A" to "B" is about 0.38 mm. The thickness of the paint at this particular location can also be estimated from the image to be about 0.28 mm. Once all the images are processed, various feature distributions, such as diameter and depth, will be analyzed. The first series of hypervelocity impact tests on targets made of materials identical to the radiator has been tentatively scheduled for February 2010. The test results will be used to convert the observed feature dimensions to the characteristics of the impacting particles and to estimate the impact condition. An effort to use the HST attitude time history to model the observed impacts has been initiated. A plan to core samples from the radiator for composition analysis is under review.

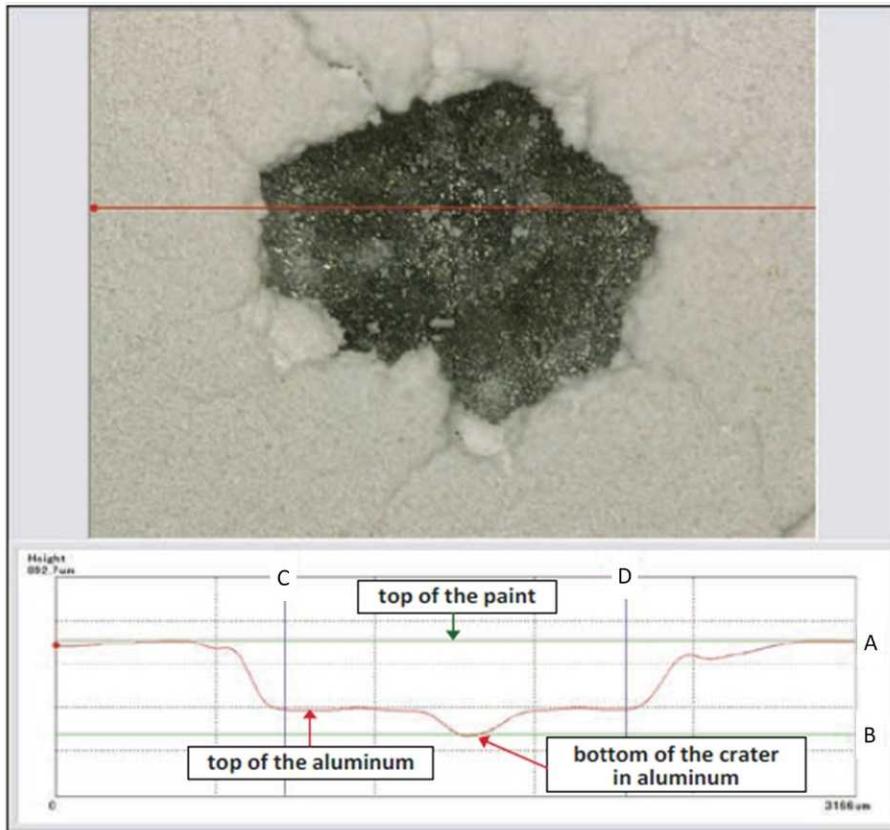


Figure 8. Digital Microscope scan of one of the larger Hubble WFPC2 MMOD impact craters. The digital microscope allows precise measurement of the height profile and other crater dimensions.

3. Future Activities

3.1 Meter Class Autonomous Telescope

NASA and the U.S. Air Force Research Laboratory are cooperating to place a wide field-of-view, 1.3 m aperture telescope on the island of Legan in the Kwajalein Atoll (167.0° E, 9.1° N) for space debris research. The MCAT system will use a Ritchey Chrétien design with a 0.9 deg FOV. The telescope will operate primarily in two different modes. During the twilight hours it will sample low inclination orbits in a “track before detect” mode. In the middle of the night it will perform a more standard GEO survey similar to MODEST. These two modes will address major limitations of the previous LEO and GEO surveys by extending the LEO survey down to 0° inclination and the GEO survey to fainter limits (~20th magnitude). The MCAT is scheduled for deployment in 2011 on Legan.

In the case of MCAT, the telescope will be conducting blind searches. For GEO searches, the search strategy will be similar to that developed for MODEST, which takes into consideration such things as solar phase angle and location of the Earth’s shadow, as well as complete coverage of the inclination versus right ascension of the ascending node (RAAN) parameter space for GEO objects.

Automation is particularly important for the low inclination searches. The track-before-detect mode searches find very limited segments of the RAAN arcs of an orbit. It is anticipated that most CCD exposures taken during low inclination searches will contain no detections. Having no human involved in either the operation of the telescope or in the data reduction and detection makes this type of search economically feasible.

3.2 Long-Term Future Activities

The NASA ODPO is researching methods for characterizing shape and material composition of orbital debris. This is extremely difficult to accomplish by remote sensing for small, unresolved targets.

NASA is building a database of computer representations of actual debris shapes. This is accomplished by using a computerized 3-dimensional scanner to scan the surfaces of fragments from ground hypervelocity impact tests. Once a digital rendition of the surface is entered, it can be manipulated by the computer to build probability density functions of brightness of the object under different viewing conditions such as observer-object-sun phase angles. It remains to be seen if different shape classes will have identifiable or unique probability density functions.

NASA is also trying to identify the material composition of debris using reflectance spectroscopy in visible and near-infrared wavelengths. Each material has specific absorption features that make it unique. NASA has built a large database of spectra from common spacecraft materials⁷. Using the absorption features, as well as slope of the spectra, NASA creates a model for material composition that best fits the spectrum taken of the object in space.

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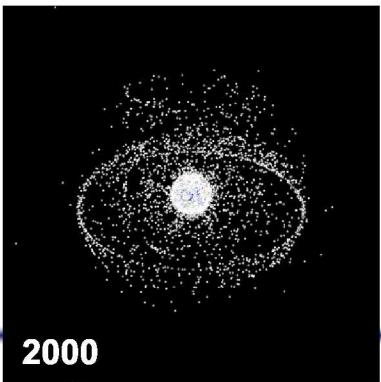
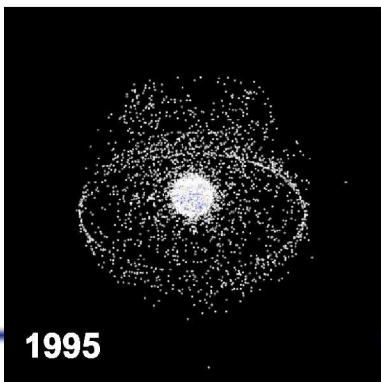
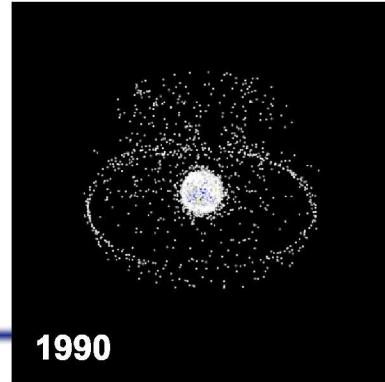
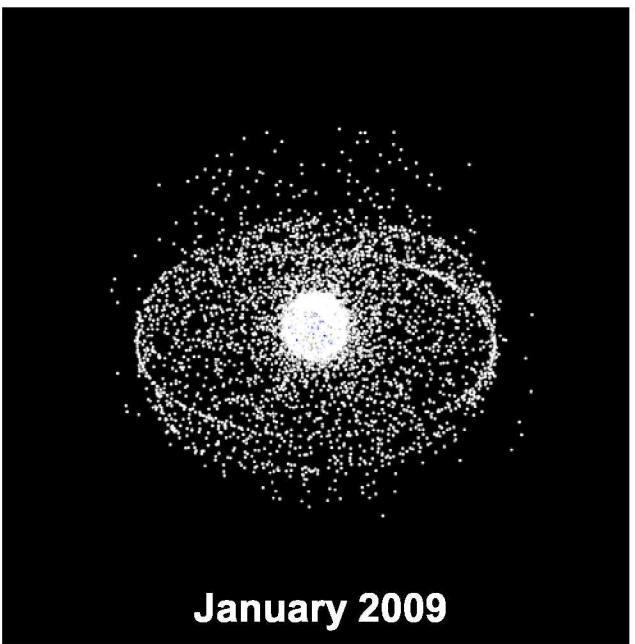
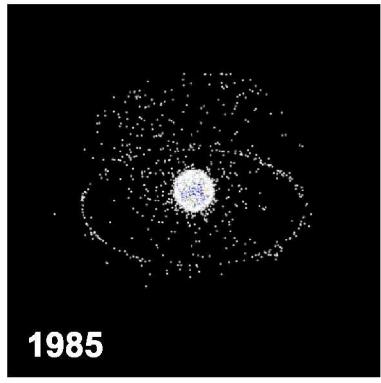
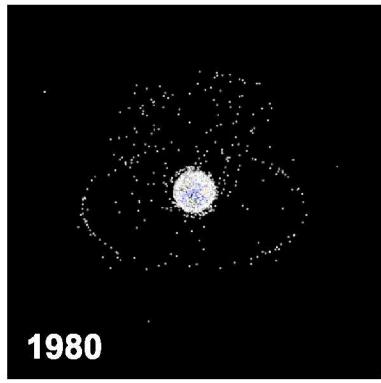
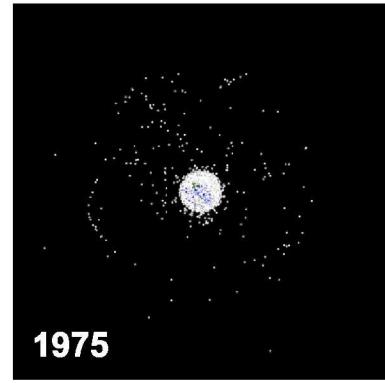
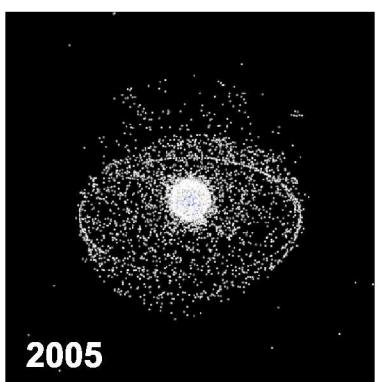
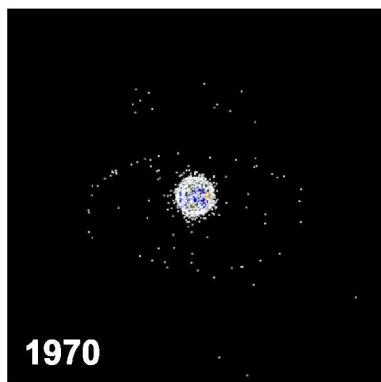
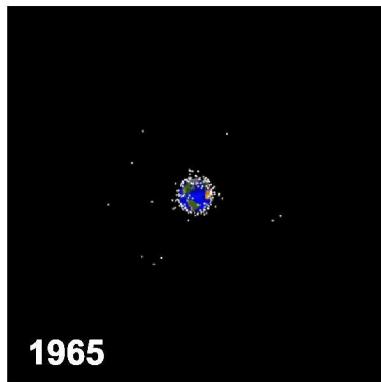
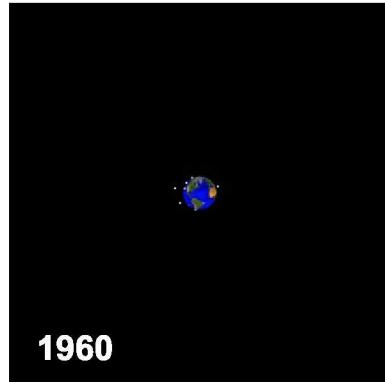
Current and Near-term Future Measurements of the Orbital Debris Environment at NASA

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**NASA Orbital Debris Program Office
Lyndon B. Johnson Space Center**

February 2010

Growth of the Satellite Population



94% of Tracked Object Population are Debris

US Space Surveillance Network

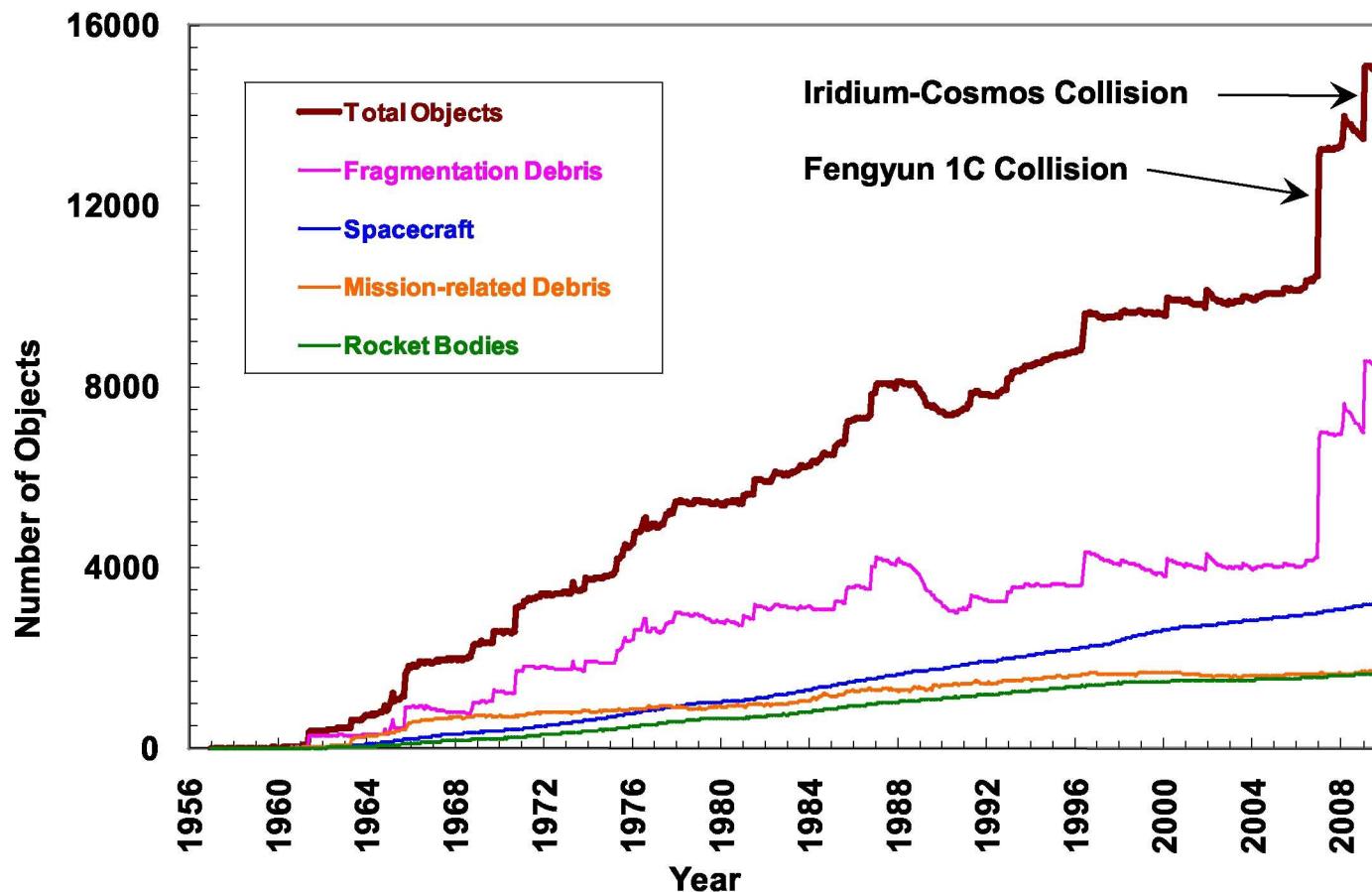


LSSC = Lincoln Space Surveillance Center
(Millstone, Haystack, HAX)
AMOS = AFRL Maui Optical & Super-computing Site
AFSSS = Air Force Space Surveillance System
MOSS = Moron Optical Space Surveillance
MSX/SBV = Mid-Course Space Experiment/Space Based Visible



Growth of the Tracked, Cataloged Population

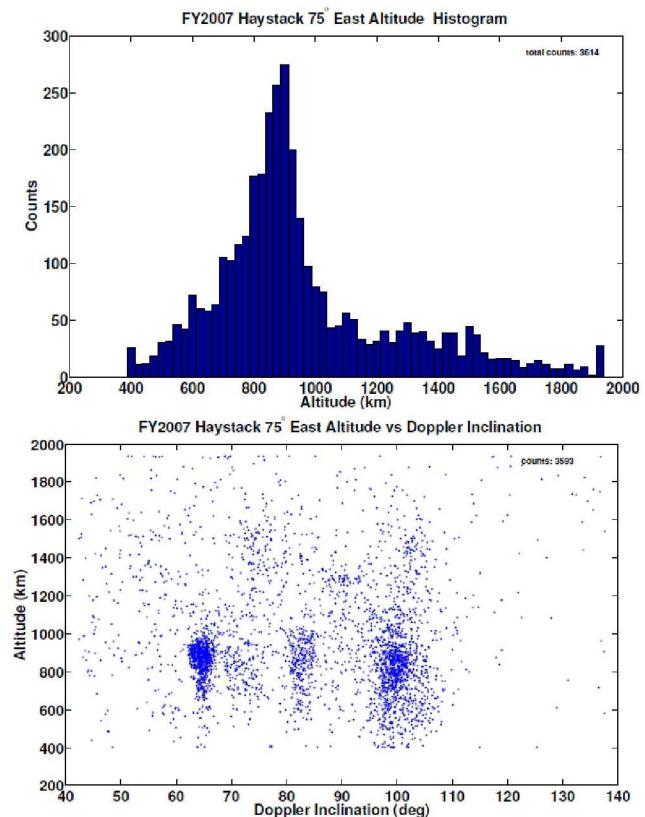
- The US Department of Defense maintains a worldwide network of sensors which catalogs and tracks man-made orbital debris
 - Although some catalogued debris is as small as 5 cm diameter, the nominal size of debris in the catalog is 10 cm in low earth orbit and 1 m at geosynchronous altitudes
 - Catalog currently has approximately 15,000 objects in orbit; 21,500 total tracked



Haystack and HAX Radars



- **Orbital Debris Radar Observations – Objective**
 - Haystack and HAX are the prime sources of data for orbital debris smaller than 10cm. Haystack and HAX collect debris data in the critical size region between 1cm and 10cm.
 - Both radars annually collect between 500 hours to 700 hours of debris observation data which provides enough statistics for developing orbital debris models.
- **Radar Description**
 - Collocated in Tyngsboro, Massachusetts at a latitude of 42.6°.
 - The main reflector of the Haystack and HAX radars are 36.6m and 12.2m diameter, respectively.
 - A pulsed continuous wave (CW) single frequency waveform is used for debris detection. Haystack transmits X-band and HAX transmits K-band.
 - Both radars observe a range window of ~ 300 to 1900 km.
 - Haystack can observe debris down to 5 mm and HAX can observe down to 2cm for LEO observations.
- **Data Collection and Processing**
 - NASA conducted the Orbital DEbris RAdar Calibration Spheres (ODERACS) experiments on two space shuttle missions in 1994 and 1995 to validate data processing at NASA JSC.
 - The experiments showed that the Haystack radar is calibrated within nominal limits, with measured RCS values accurate to $\pm 1.5\text{dB}$.





Goldstone Radar

• Goldstone Radar Overview

- The NASA Jet Propulsion Laboratory Goldstone radar is used on a limited basis to supplement orbital debris observations made by Haystack and HAX.
- Collects up to 100 hours of data annually
- Goldstone provides a measurement of the debris environment between 2 mm and 1 cm.

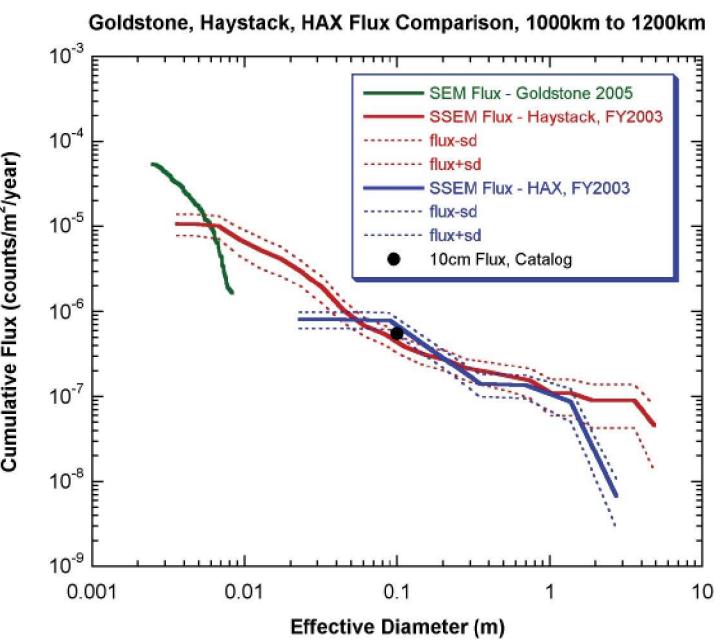


Radar Description

- Collocated in southern California's Mojave desert at a latitude of 35.2°.
- Pairs of up chirp and down chirp X-band pulses are used for debris detection.
- Observable range window of ~ 350 to 3300km.
- Observable range rates of 0.85km/s.
 - This dictates a staring observation mode near the zenith which makes Doppler inclination measurements unreliable.
 - Upgrades to the data acquisition system are currently being tested to increase the observable range rates. This would allow pointing away from the zenith and hence a reliable Doppler inclination measurement.
- The radar cross section measurements have greater uncertainties than that of Haystack or HAX since the Goldstone radar:
 - does not calibrate using a calibration satellite
 - does not have a monopulse system to determine the position of the debris within the radar beam.

Data Collection and Processing

- The data collected at the radar is processed at JSC using software supplied by JPL.
- The processed data is thoroughly inspected at JSC for quality control before subsequent extensive analysis.

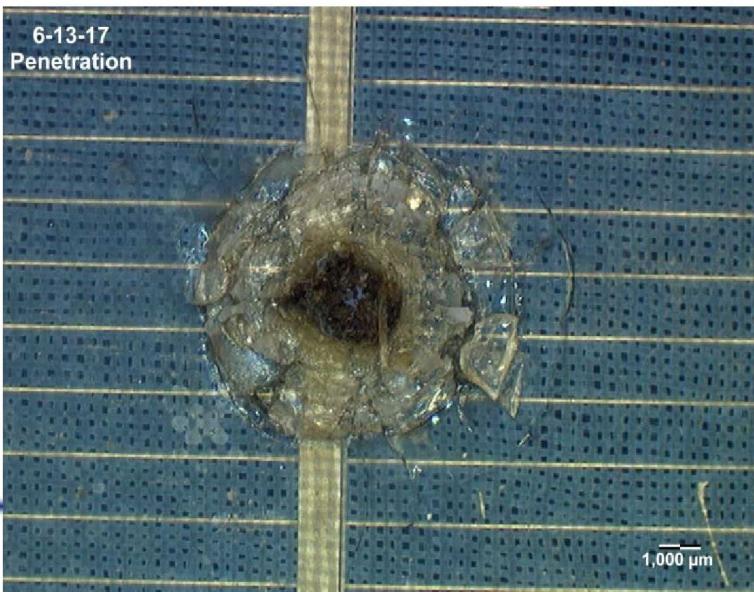
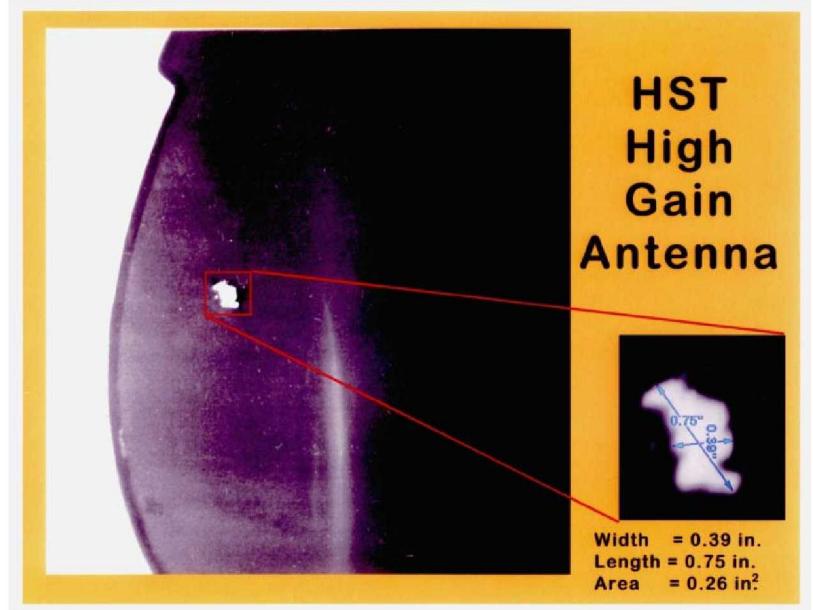




Spacecraft Surface Photo Surveys

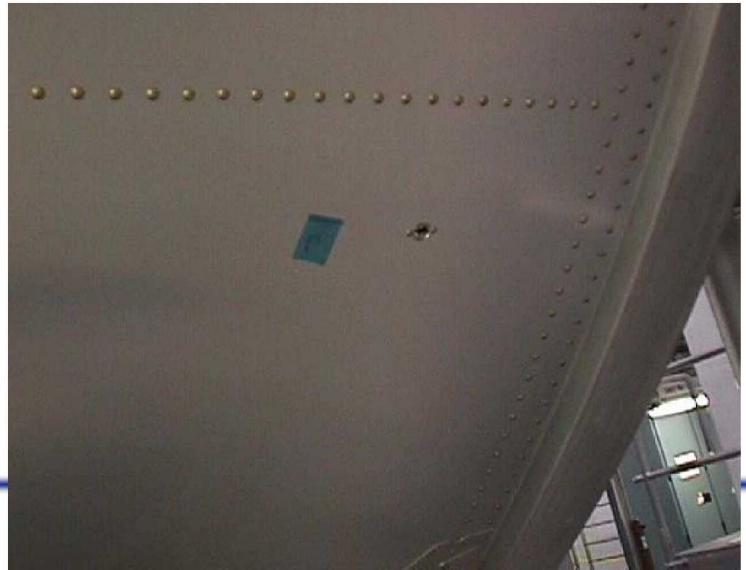


HST



Mir

ISS
MPLM

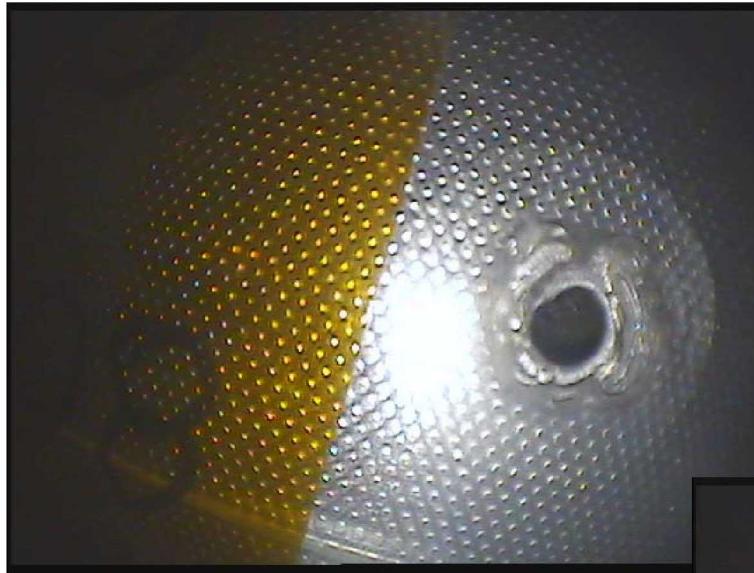




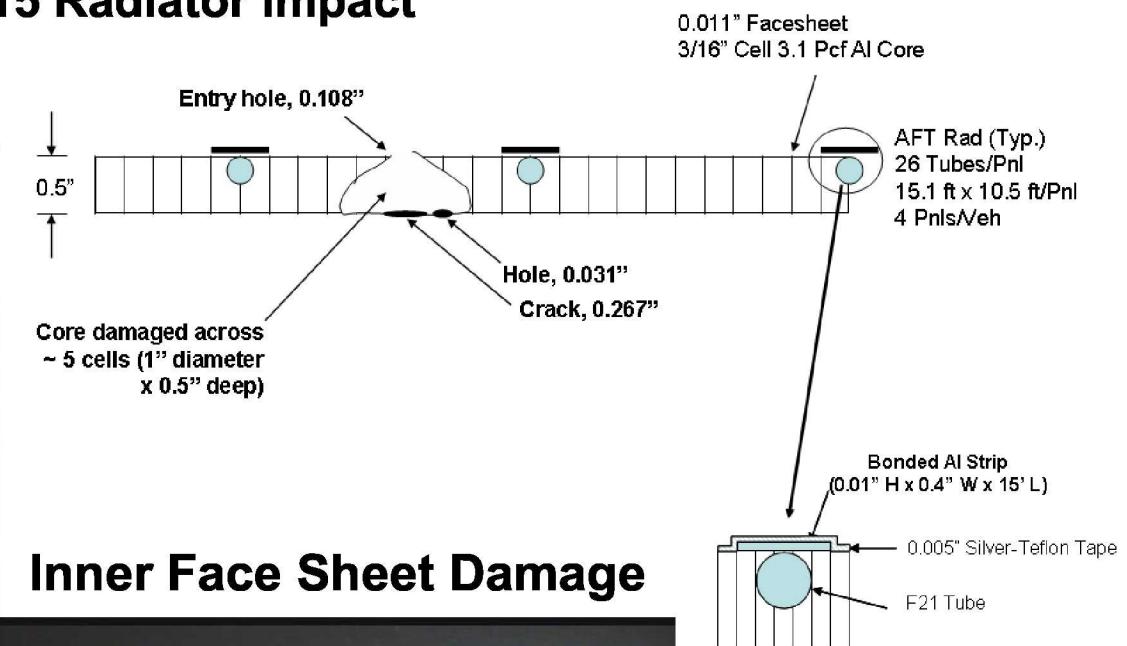
Examination of Returned Surfaces

STS-115 Radiator Impact

Outer Face Sheet Damage



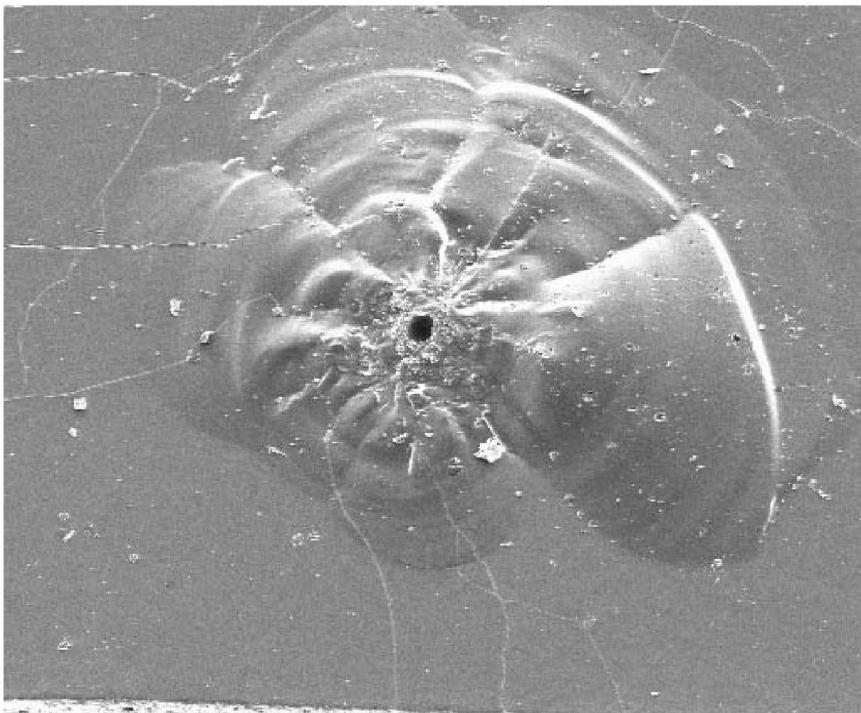
Estimated impactor
size = 1.5 - 2.0 mm



Inner Face Sheet Damage

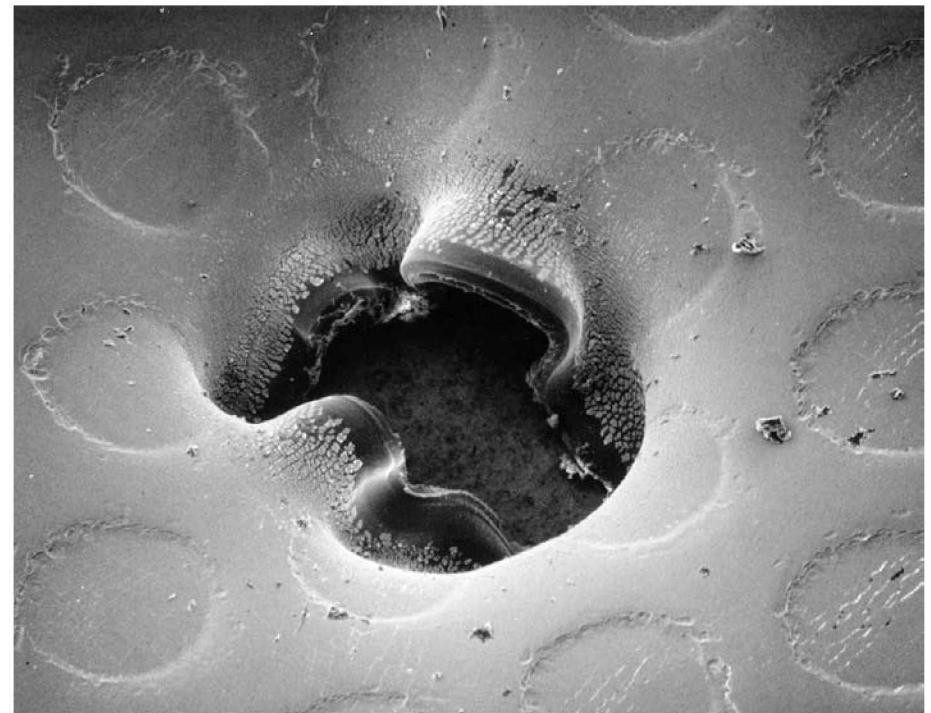


Examination of Returned Surfaces



STS-92 Window Impact

~0.1 mm Aluminum Debris
2 mm diameter crater



STS-90 Radiator Penetration

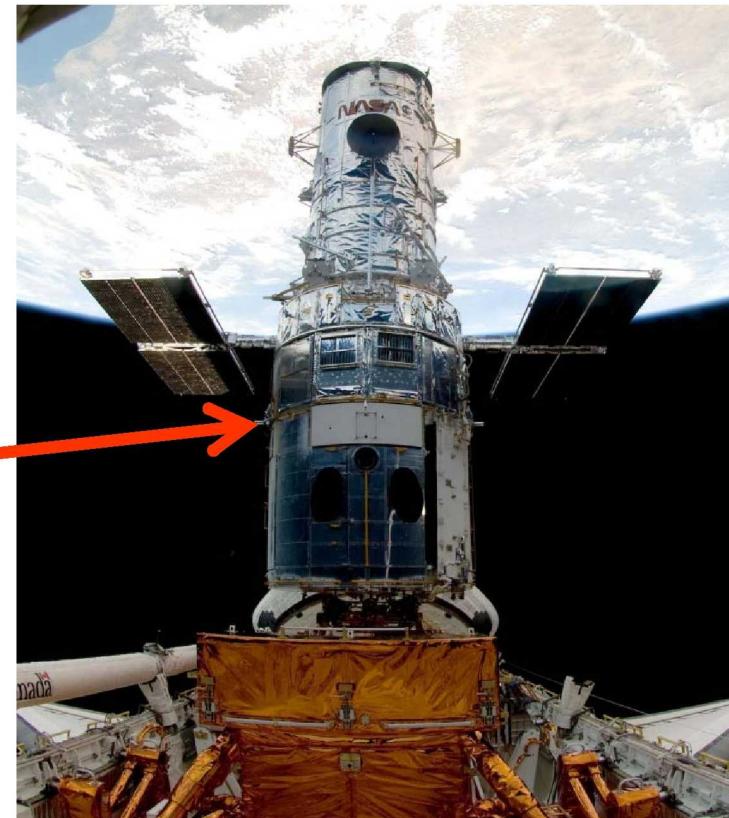
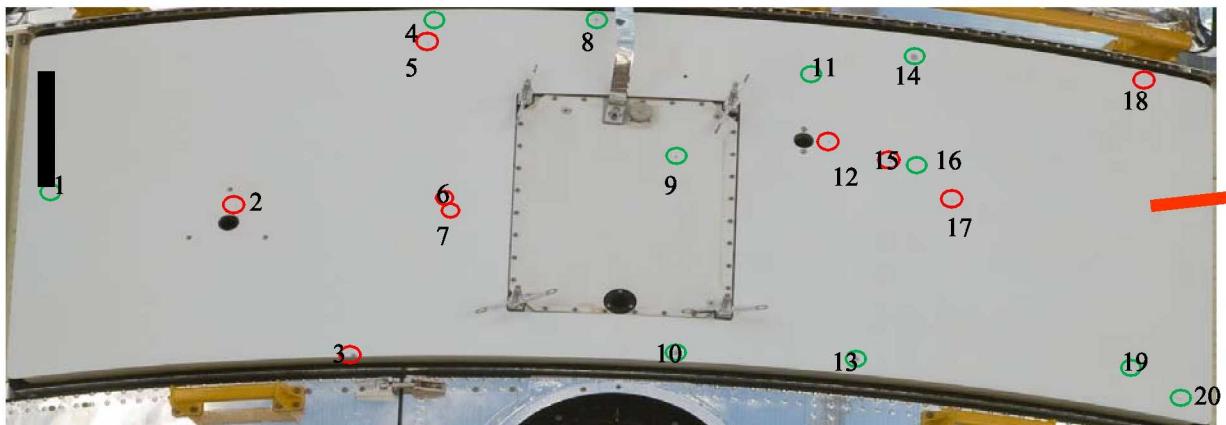
~0.3 mm Paint Particle
1 mm diameter hole



Examination of Returned Surfaces

Hubble Wide Field Planetary Camera 2 (WFPC2) Radiator

- Exposed to space for 15 years, 7 months
 - Installed during servicing mission 1, December 1993
 - Returned to Earth May 2009 by STS-126
- Will examine and measure each crater larger than ~100 µm
- Will core selected impact features for chemical analysis



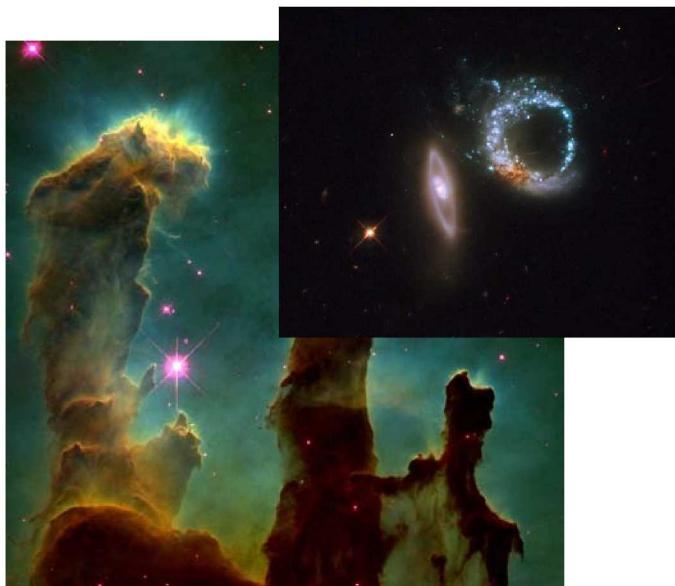
- Red circles: Impacts identified from 2002 repair mission images
- Green circles: Impacts identified from 2009 images



Examination of Returned Surfaces

Hubble Wide Field Planetary Camera 2 (WFPC2) Radiator

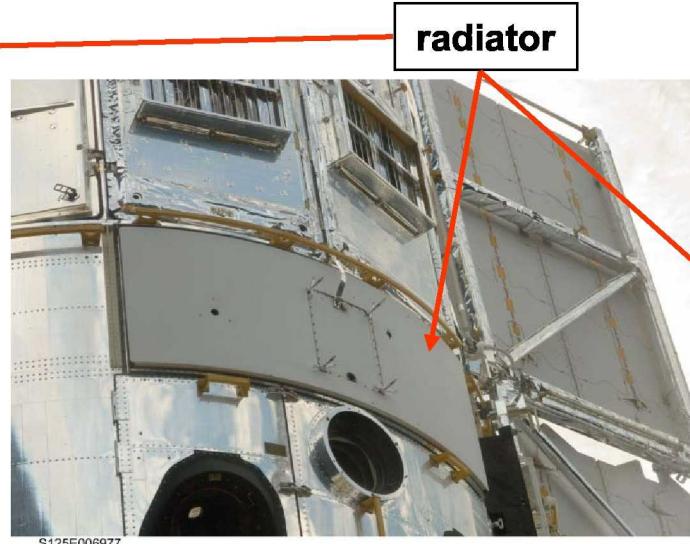
- HST was launched from Discovery on 24 April 1990
- WFPC1 was replaced by WFPC2 during STS-61 HST Servicing Mission 1 (SM1) in December 1993
 - WFPC2 is the "workhorse" instrument behind nearly all of the most famous Hubble pictures
- WFPC2 was replaced by WFC3 during STS-125 HST SM4 in May 2009



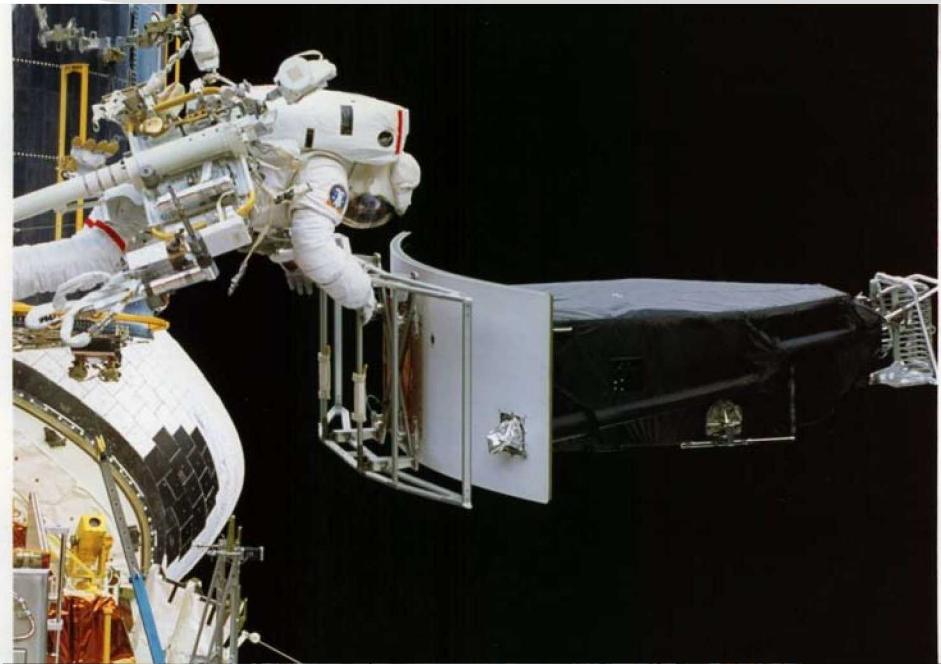


WFPC2 Radiator Background

- The WFPC2 radiator was in space for 15.5 years (3.6 years for WFPC1 radiator)
- Dimensions of the radiator: 0.8 m × 2.2 m
- Outer layer: an aluminum plate (4.06 mm thick) coated with 4~8 mils Zinc Orthotitanate (ZOT, a ceramic thermal control paint)



HST SM4 (STS-125, May 2009)

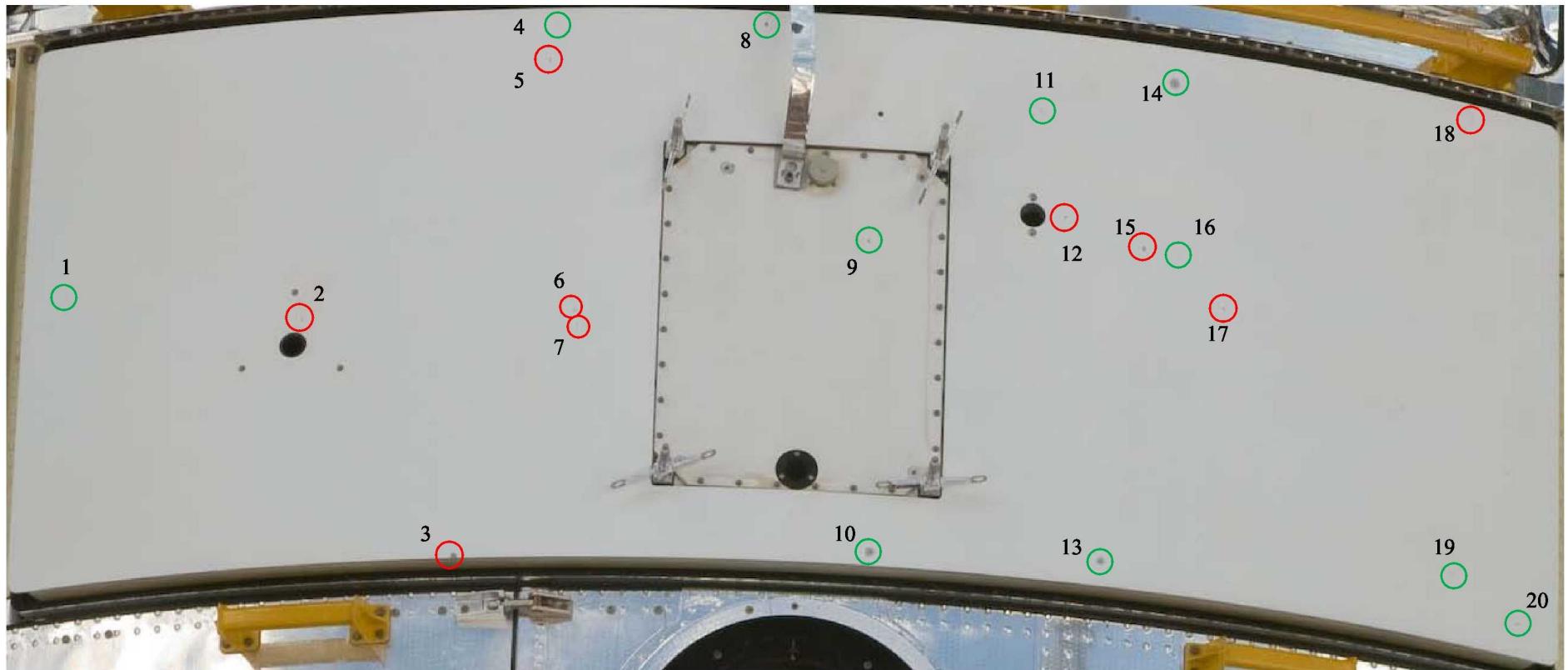


S125E006996



S125E007168

Visible MMOD Impacts from the On-orbit Imagery Survey



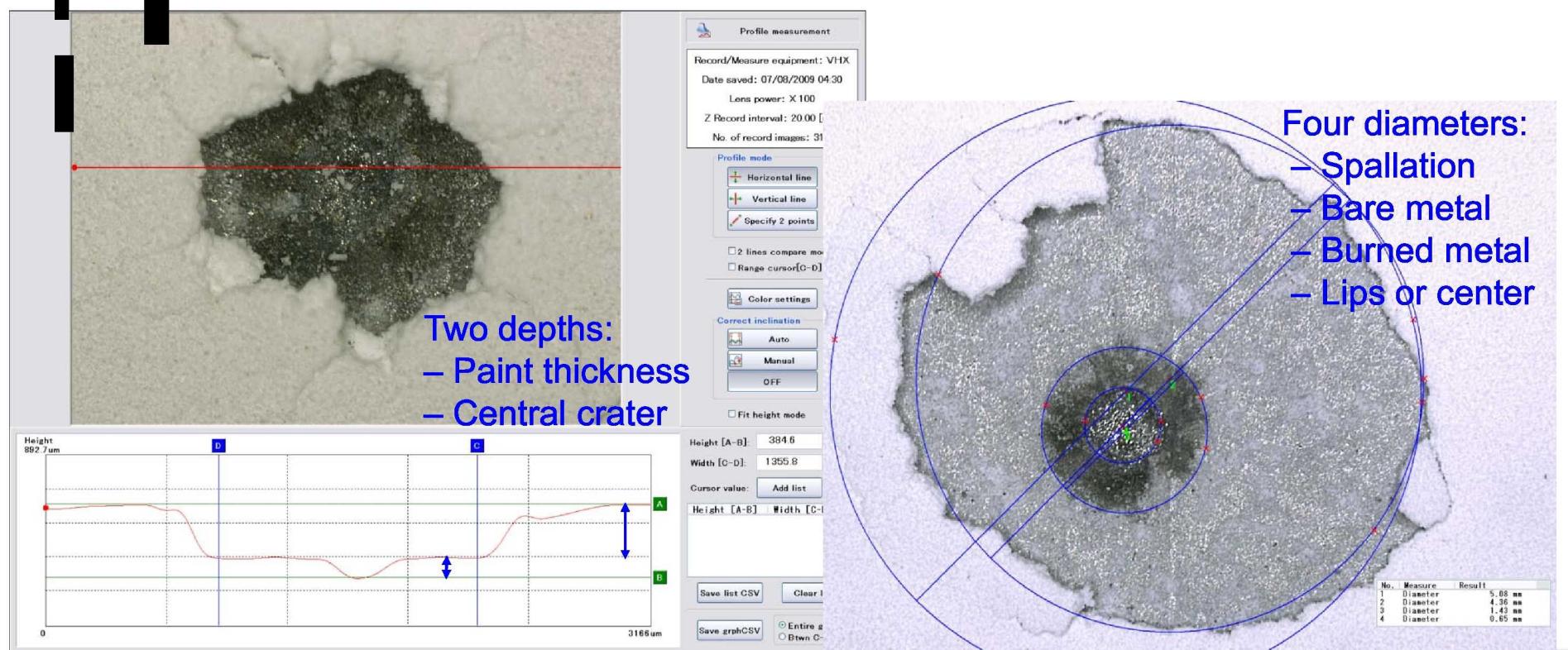
S125e006995.jpg (edited)

- Red circles: Impacts identified from SM3B images (2002)
- Green circles: Impacts identified from SM4 images (2009)

Inspection Results and Data Processing



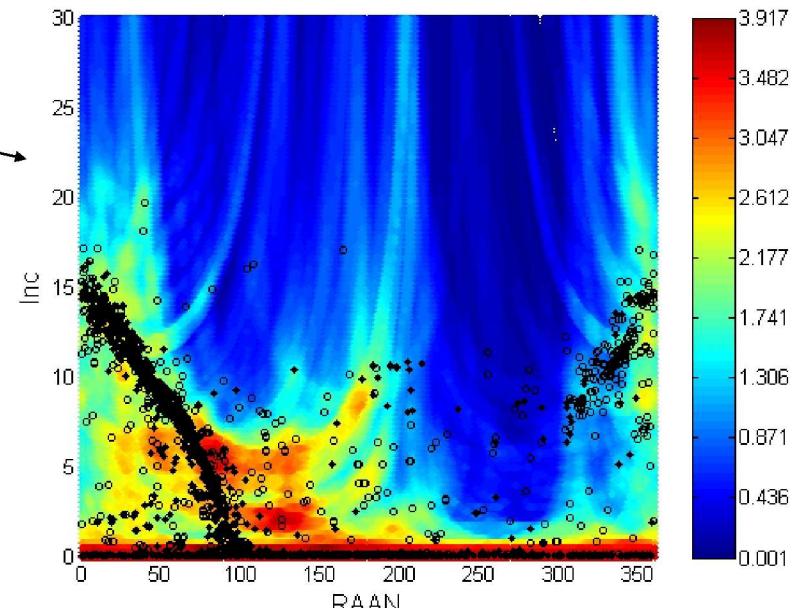
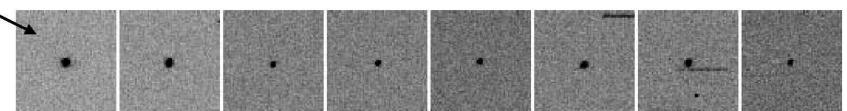
- Documented 685 impact craters ($\geq 300 \mu\text{m}$) and numerous non-impact features
- No through-hole
- The largest one: 1.6 mm crater plus 1.4 cm spall zone



Michigan Orbital Debris Survey Telescope (MODEST)



- GEO debris survey telescope (0.6/0.9 Schmidt Telescope)
- Located near La Serena, Chile at the Cerro Tololo Inter-American Observatory (CTIO)
- Collecting data since 2002
- Data used in modeling of the future environment (sample data shown middle right)
- Limiting Magnitude $\sim 19 M_v$ in R (corresponding to a size of 30 cm if you assume 0.13 albedo)
- Figure (bottom right) shows a probability map of where we have looked and the detections seen
 - Red shows the orbit planes that were the most visible, while blue shows the orbit planes that were the least visible
 - Solid diamonds are correlated targets and the open circles are uncorrelated targets
- Status of Survey Project
 - Collecting survey data every observing run
 - Collecting light curve data in specific photometric bands on uncorrelated targets
 - Use of two telescopes to refine orbits and the orbit determination process
- Special Projects – High Area-to-Mass (A/m)
 - Joint project through IADC for objects of high A/m
 - Following IADC high A/m objects at sites around the world for a more complete orbit
 - Efforts being made to determine source and material of these objects

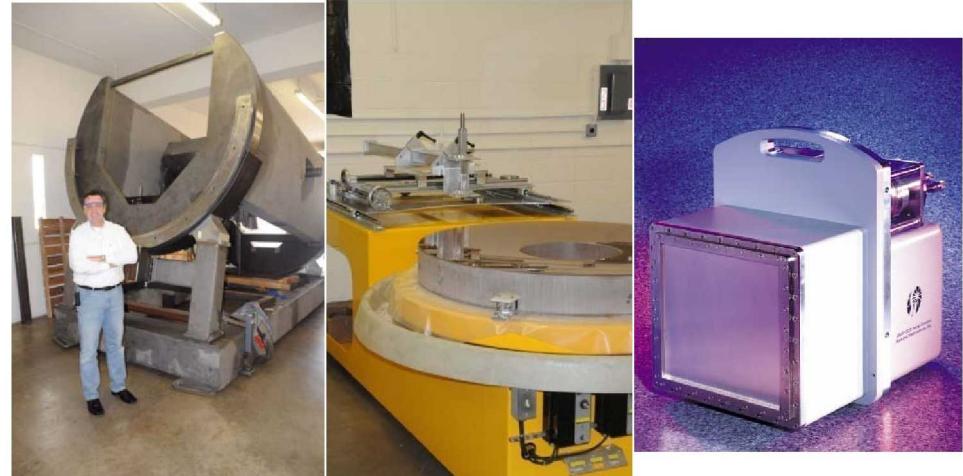


GEO/LEO Observations from Kwajalein Atoll



- Meter Class Autonomous Telescope (MCAT)

- Designing a 1.3 m, 0.96 deg FOV autonomous survey telescope to be installed 3Q 2010) for detection and multi-spectral (Optical/NIR) photometry of targets to 20th magnitude (10 cm diameter)
- 4Kx4K 15 um pixel CCD; 4-port, TDI enabled, Cryo-Tiger cooled; 3 e⁻ read noise @ 100 KHz; Broad Band coated (360 nm -1 um)



I GEO

- Comprehensive assessment of debris environment
 - High A/m debris
 - Determination of orbital parameters as inputs to NASA's environment model

I LEO

- MCAT will detect new LEO debris and enable a statistical assessment of the low-inclination (0-20 deg) debris environment in the 1-10 cm diameter size regime

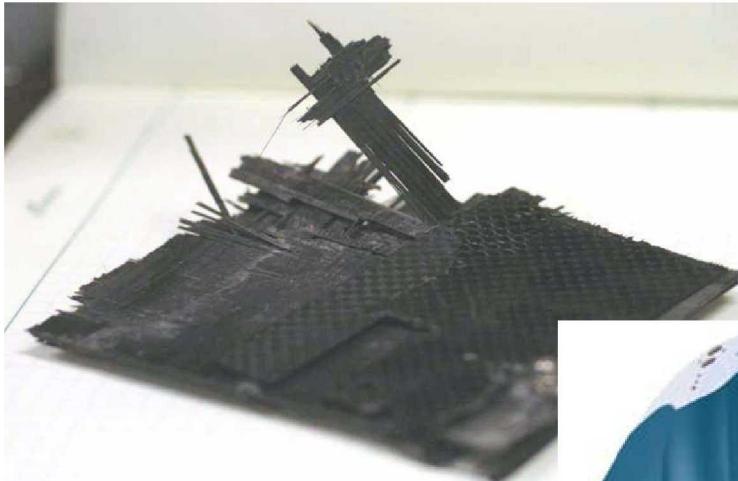


Optical Size and Shape Determination



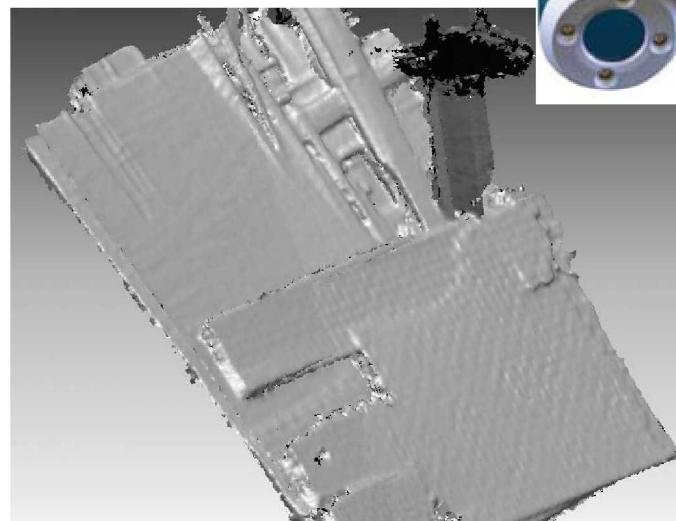
• Goal

- To develop a optical size estimation model comparable to the existing radar size estimation model .
- To look for differences in the optical probability distributions of different classes of objects.



• Current work

- Complex 3-D shapes cannot be easily described mathematically although they can be grouped into broad categories such as nuggets, flakes, etc.
- Scanner can take many realistic shapes which can be grouped into these shape classes.
- Characteristic length of each sample is measured, where X, Y, Z are the three orthogonal projections of a object as seen in top figure.
 - $L_c = 1/3(X+Y+Z)$



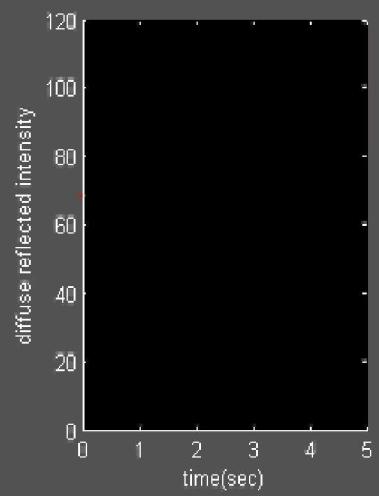
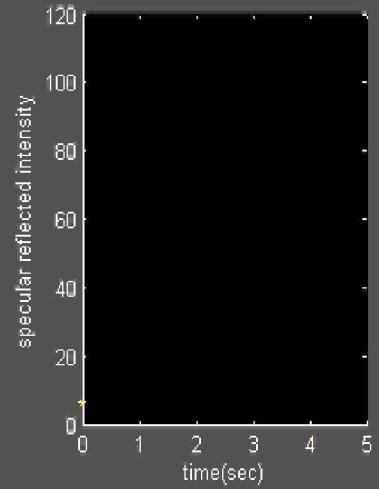
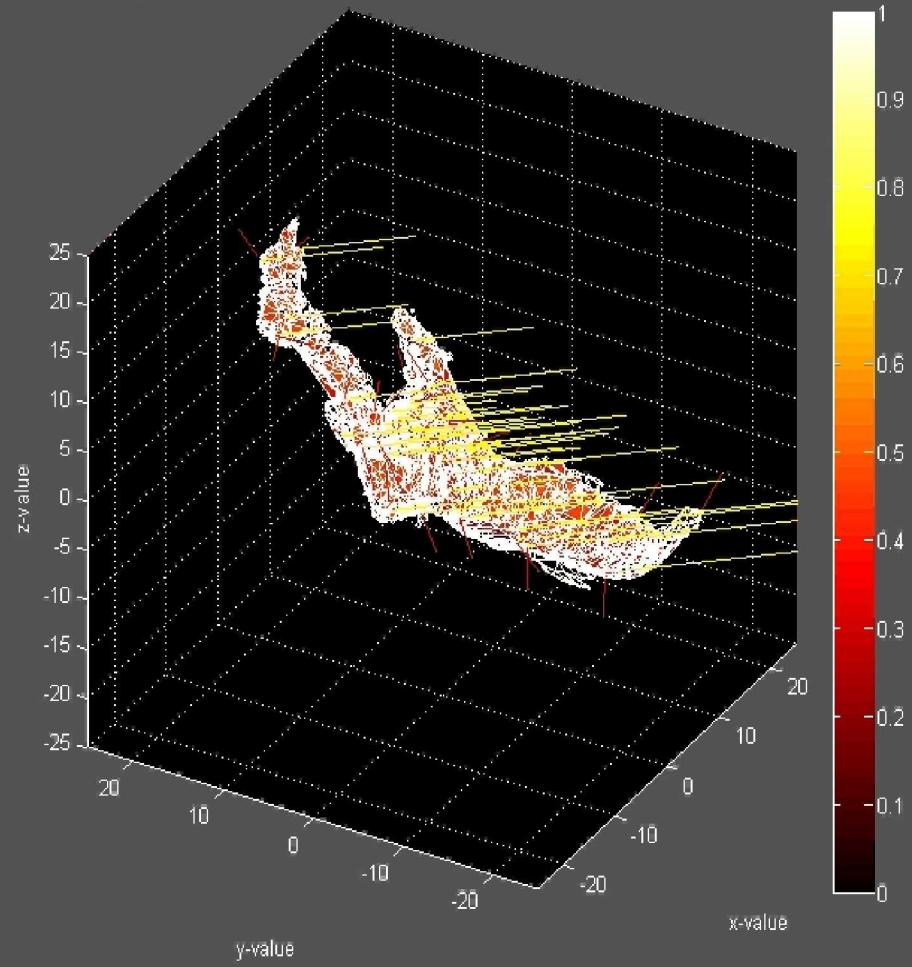
• Future work

- Shapes can be manipulated in software to produce photometric response as a function of viewing geometry for all orientations of the object.
- The photometric response and the specular / diffuse ratio can be calibrated in the laboratory.

Computer Generated Light Curves from Scanned Fragments



Fragment 30; phase angle=19.4539 degrees. nobs=(-0.75 -0.43301 0.5) nsun=(-0.5272 -0.68706 0.5)



Spectral Studies



- **Use reflectance spectroscopy in the visible and near-infrared to determine the surface material of space objects**
 - Knowledge of material yields better size estimation data
- **Each material has specific absorption features that make it unique**
 - Using those features, as well as slope, creates a model for materials that best fits the spectrum taken of the object in space
- **Results**
 - Placed objects into categories based on spectral response
 - See example on top right, where the object was thought to be either an asteroid or a human-made object
 - Determined to be human-made due to spectral signature of white paint
 - Measured pristine spacecraft prior to launch and looked at space weathering of materials
 - See example at the bottom right, where the model is based on pre-flight measurements showing great agreement in slope and absorption features
 - Received first data on debris objects (all large pieces)
- **Status of the project – Work in Progress**
 - Continued material modeling
 - Determine cause of the unexpected increase in slope for remote measurements as compared to laboratory measurements
 - Taking ground truth data on spacecraft prior to launch to get better idea of changes in material spectra
 - Obtain more remote measurements of catalogued objects and debris

